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# Residue management and tillage effects on soil-water storage and grain yield of dryland wheat and sorghum for a clay loam in Texas

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**Abstract**

Dryland wheat (*Triticum aestivum* L.) and grain sorghum (*Sorghum bicolor* (L.) Moench) are often grown using a wheat–sorghum-fallow (WSF) crop rotation on the semiarid North American Great Plains. Precipitation stored during fallow as soil water is crucial to the success of the WSF rotation. Stubble mulch-tillage (SM) and no-tillage (NT) residue management practices reduce evaporation, but the sparse residue cover produced by dryland crops, particularly sorghum, is insufficient to reduce soil crusting and runoff. Subsoil tillage practices, e.g., paratill (PT) or sweep (ST), fracture infiltration limiting soil layers and, when used with residue management practices, may increase soil-water storage and crop growth. Our objectives were to compare the effects of PT to 0.35 m or ST to 0.10 m treatments on soil cone penetration resistance, soil-water storage, and dryland crop yield with NT and SM residue management. Six contour-farmed level-terraced watersheds with a Pullman clay loam (US soil taxonomy: fine, mixed, superactive, thermic Torrertic Paleustoll; FAO: Kastanozems) at the USDA—Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, TX, USA (35°11′N, 102°5′W) were cropped as pairs using a WSF rotation so that each phase of the sequence appeared each year. In 1988, residue management plots received PT or ST every 3 years during fallow after sorghum resulting in five treatments: (i) NT–PT, (ii) NT–NOPT, (iii) NT–ST, (iv) SM–PT, and (v) SM–NOPT. Cone penetration resistance was the greatest in NT plots and reduced with PT after 12, 23, and 31 months. Mean 1990–1995 soil-water storage during fallow after wheat was greater with NT than with SM, but unaffected by PT or ST. Dryland wheat and sorghum grain yields, total water use, and water use efficiency (WUE) were not consistently increased with NT, however, and unaffected by PT or ST tillage. We conclude, for a dryland WSF rotation, that: (1) NT increased mean soil-water storage during fallow after wheat compared to SM, and (2) ST and PT “subsoil” tillage of a Pullman did not increase water storage or yield. Therefore, NT residue management was more beneficial for dryland crop production than subsoil tillage.
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*Keywords:* No-tillage; Stubble mulch-tillage; Penetration resistance; Crop rotation

## 1. Introduction

On the semiarid North American Great Plains, wheat (*Triticum aestivum* L.) and grain sorghum (*Sorghum bicolor* (L.) Moench) are grown under

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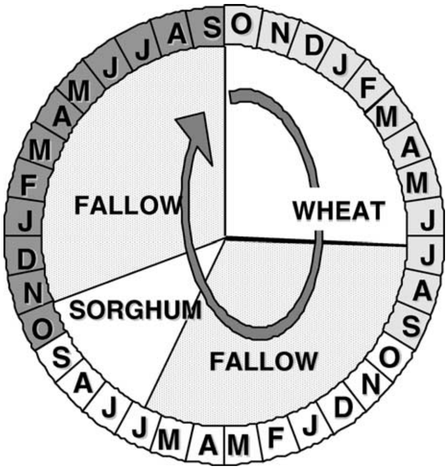


Fig. 1. The WSF rotation diagramed as a 3-year cycle beginning with wheat establishment in October (top). Wheat is harvested 10 months later in July and the soil is fallowed until June of the second year (11 months) when grain sorghum is grown using soil water stored during fallow to augment summer rainfall. After sorghum harvest in November of the third year the soil is again fallowed for 10 months when wheat is planted and the cycle repeated.

dryland conditions using the wheat–sorghum-fallow (WSF) crop rotation described by Jones and Popham (1997). This cropping sequence produces two crops, sorghum and wheat, with two intervening 11-month fallow periods during a 3-year cycle (Fig. 1). Precipitation stored as soil water during fallow after wheat or sorghum harvest is crucial to the success of the WSF cropping sequence. Water storage with the WSF crop rotation has been improved by using management practices that retain more residues on the soil surface, thus achieving steadily greater grain yields as accumulated residue increases (Unger and Baumhardt, 1999).

The two principal residue management practices used with WSF are stubble mulch-tillage (SM) and no-tillage (NT). Both water conservation practices reduce evaporation and improve precipitation storage by retaining residues on the soil surface (Steiner, 1994). Under dryland conditions, wheat and sorghum usually produce insufficient residue to intercept the raindrop impact that results in soil crusting and reduced infiltration (Baumhardt et al., 1993; Baumhardt and Lascano, 1996). Consequently, rain infiltration into soil managed with NT is typically lower than with SM, which fractures soil crusts and reduces storm runoff (Jones et al., 1994). Coupling NT residue management practices with subsoil tillage may improve infiltration and root distribution in clay loam soils and, therefore, increase available soil water and crop yields.

Subsoil tillage methods are used to fracture root or water restricting layers (Salokhe, 2000) while improving surface residue retention. For example, paratill (PT) does not incorporate residues, but increases soil porosity, water infiltration, and root penetration (Mukhtar et al., 1985; Busscher et al., 1988; Clark et al., 1993). Similar initial reductions in soil density and penetration resistance have been reported (Unger, 1993; Unger and Jones, 1998) to a depth of 0.3 m with PT on a Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll) compared to NT plots for up to 4 years. The potential amount of water available for crop use increases as the amount of soil explored by a plant root system increases. Penetration resistance was reduced and yield increased in wheat, soybean (*Glycine max* L. Merr.) and corn (*Zea mays* L.) when using subsoil tillage to fracture dense layers formed after tillage in a loamy sand soil (Busscher et al., 2000, 2001). In contrast, Pikul and Aase (1999) reported no differences in wheat yields on sandy loam soils, but soil properties were improved from residual PT effects for 2.5 years.

We hypothesized that occasional PT would increase soil-water storage on dryland through increased rain infiltration and improve crop yields by loosening the subsoil for greater root exploration volume and extraction of soil water. Our objectives were to determine the effects of subsoil PT and sweep tillage (ST) used with SM or NT residue management on cone penetration resistance into a clay loam soil, soil-water storage, and yield of dryland wheat and sorghum grown in the WSF cropping sequence.

## 2. Materials and methods

### 2.1. Experimental

Tillage and residue-management effects on soil penetration resistance, storage of precipitation as soil water during fallow, and the yield and water use efficiency (WUE) of wheat and grain sorghum were evaluated at the USDA—Agricultural Research Service, Conservation and Production Research Laboratory,

Table 1
Chemical weed control applications for the NT, residue management system used with the 3-year WSF rotation at Bushland, TX

| WSF rotation sequence stage | Chemical application |
|---|---|
| Fallow wheat harvest (July, Y1) | 3.36 kg a.i. $ha^{-1}$ atrazine[a], 0.84 kg a.i. $ha^{-1}$ 2,4-D[b] |
| Before sorghum planting (June, Y2) | 0.56 kg a.i. $ha^{-1}$ glyphosate[c] |
| Seasonal weed control in sorghum (June, Y2) | 1.68 kg a.i. $ha^{-1}$ propazine[d] |
| Mid-fallow sorghum (February, Y3) | 0.023 kg a.i. $ha^{-1}$ chlorosulfuron[e], 0.37 kg a.i. $ha^{-1}$ 2,4-D |
| Before wheat planting (October, Y3) | 0.56 kg a.i. $ha^{-1}$ glyphosate |
| Any weed control during fallow periods | 0.56 kg a.i. $ha^{-1}$ glyphosate, 0.37 kg a.i. $ha^{-1}$ 2,4-D |

[a] 6-Chloro-*N*-ethyl-*N*′-(1-methylethyl)-1,3,5-triazine-2,4-diamine.
[b] (2,4-Dichlorophenoxy) acetic acid.
[c] *N*-(Phosphonomethyl) glycine.
[d] 6-Chloro-*N*,*N*′-bis (1-methylethyl)-1,3,5-triazine-2,4-diamine.
[e] 2-Chloro-*N*[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl] benzenesulfanomide].

Bushland, TX, USA (35°11′N, 102°5′W). The research was conducted from 1988 to 1995 on six contour-farmed level-terraced watersheds, described by Hauser et al. (1962), ranging in area from 2.3 to 4.1 ha with gently sloping (1–2%) Pullman clay loam (US soil taxonomy: fine, mixed, superactive, thermic Torrertic Paleustoll; FAO: Kastanozems) described by Unger and Pringle (1981). Terrace intervals were cropped in a WSF rotation with each phase of the WSF sequence present as main plots in two watersheds each year. Winter wheat, TAM 107[1] (Foundation Seed, College Station, TX), was sown on all wheat plots in late September or early October at a 40 kg $ha^{-1}$ rate to achieve $2.5 \times 10^6$ plants $ha^{-1}$ using a high-clearance grain drill with hoe openers and press wheels at a 0.3 m row spacing. Grain sorghum, Dekalb hybrid "DK41Y" (DeKalb, Illinois), was seeded in 0.75 m rows during early to mid-June at 80,000 seeds $ha^{-1}$, using 'Max-Emerge™' (John Deere, East Moline, IL) unit planters. Growing season weed control for sorghum consisted of 1.7 kg a.i. $ha^{-1}$ propazine (6-chloro-*N*,*N*′-bis(1-methylethyl)-1,3,5-triazine-2,4-diamine) applied pre-emergence. Control of flixweed (*Descurainia sophia* (L.) Webb ex Prantl) in growing wheat required 0.6 kg a.i. $ha^{-1}$ 2,4-D ((2,4-dichlorophenoxy) acetic acid) applied in late February during some years.

These three paired-watersheds received SM or NT residue management. With SM, weeds were controlled as needed during the fallow season (3–4 tillage operations) using a 4.6 m wide Richardson (Sunflower Man, Beloit, KS) sweep-plow at a depth of 0.10 m. It had one 1.5 and two 1.8 m wide overlapping V-shaped blades and was fitted with a trailing mulch treader. Weeds were chemically controlled with NT (Table 1), resulting in no soil disturbance, except for seeding the crops. During the fallow after sorghum-harvest phase of the WSF rotation, paratillage treatments (PT, paratill; NOPT, no paratillage) were imposed on 35 m × 40 m plots every 3 years beginning in April and December 1988, and November 1989. The PT implement (Tye, Lockney, TX), consisting of four center-faced paratill shanks and coulters with the points at 0.6 m intervals (Fig. 2) was operated at 1.3 m $s^{-1}$ speed and 0.35 m depth. At the same time, an additional one-time sweep-plow tillage treatment (ST) was applied to otherwise NT residue management plots. The resulting residue management and tillage treatments of (i) NT–PT, (ii) NT–NOPT, (iii) NT–ST, (iv) SM–PT, and (v) SM–NOPT were replicated four times within paired-watersheds. Measured treatment effects were compared according to a randomized complete block analysis of variance (ANOVA) using SAS-PROCGLM (SAS, 1988).

### 2.2. Measurements

Soil-water content was sampled gravimetrically after fallow, i.e., at planting and after harvest using duplicate soil cores taken within the plots to a depth of 1.8 in 0.3 m increments. Volumetric soil water was then calculated using these gravimetric samples

[1] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA—Agricultural Research Service. Mention of a pesticide does not constitute a recommendation for use nor does it imply registration under FIFRA as amended.

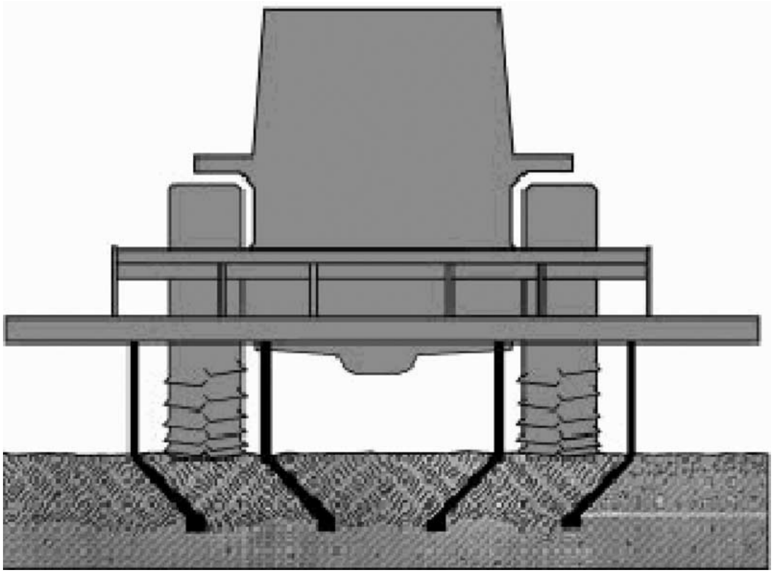

Fig. 2. Diagram of a paratill implement configured with four shank-shatter plate assemblies faced toward the center and adjusted for total loosening.

and previously measured soil density as described in Jones et al. (1994). Precipitation storage during fallow, soil-water content at planting, and crop water use is reported as plant-available soil water (water held between 0.03 and 1.5 MPa suction). Precipitation was measured using a standard rain gauge adjacent to the plots and runoff was contained within contours of the level terraces. Under dryland conditions we estimated annual drainage from the unsaturated hydraulic conductivity to be negligible (<17 mm per year), which is consistent with the negligible drainage measured in nearby 2.4 m deep by 9 $m^2$ lysimeters receiving irrigation (S.R. Evett, pers. commun.). We calculated fallow precipitation storage as the difference in initial soil-water content at harvest and at the end of fallow. Tillage treatment effects on water storage during fallow were compared according to a randomized complete block analysis using the initial water content as a covariant. Crop water use during the growing season was calculated as the sum of precipitation and the difference between soil-water content at planting and harvest. Wheat and sorghum grain yields, reported at standard moisture of 130 g $kg^{-1}$, were determined by combined harvesting the entire plot.

Indexed cone penetration resistance, i.e., force per unit basal area, and soil-water content were measured in November of 1995 after two full rotation cycles and, corresponding paratill operations. Measurements were taken within plots of all three-rotation phases approximately 12, 23, and 31 months after PT and ST treatments. We used the same tractor mounted hydraulically driven penetrometer as Allen and Musick (1997), which was similar to that described by Williford et al. (1972). Penetration resistance of the 30°, included angle, 20.3 mm diameter cone-tip was recorded with depth to 0.51 m in 0.063 m increments at four subsample sites between non-traffic crop rows. Soil-water content to 0.51 m depth was determined from soil cores taken in adjacent areas and converted to a volumetric basis. Tillage treatment effects on penetration resistance were compared by depth interval according to a randomized complete block analysis using soil-water content as a covariant.

## 3. Results and discussion

### 3.1. Penetration resistance

The cone soil penetration resistance index was compared in NT and SM residue management plots 12, 23, and 31 months after NOPT, PT, and ST subsoil tillage

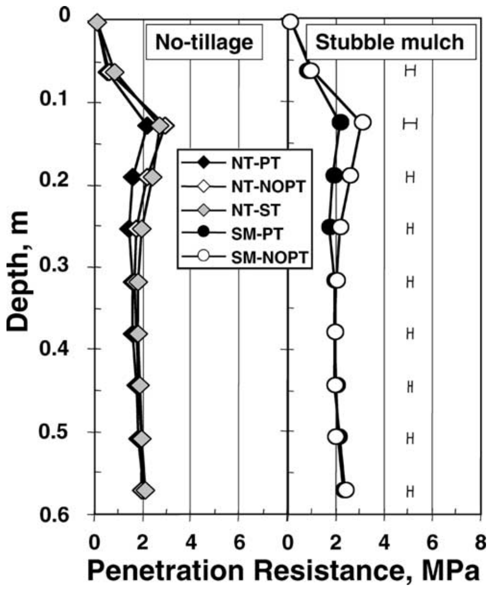


Fig. 3. Mean soil penetration resistance measured 12 months after treatment, plotted with depth for NT residue management plots receiving NOPT, PT, and ST, and for SM residue management plots receiving NOPT and PT. Error bars represent the pooled LSD ($P < 0.05$) by depth for all treatments.

treatment for all the three phases of the WSF cropping sequence. Soil cone penetration index, measured 12 months after tillage treatment, is plotted to a depth of 0.6 m for SM and NT residue management systems in Fig. 3. These measurements were taken immediately after wheat had been seeded in moist soil following fallow after sorghum. Little difference in cone index was apparent above the 0.10 m depth between residue management practices for any tillage treatment. However, the clayey subsoil layer, natural soil consolidation, or the effects of repeated tillage tool use increased cone index immediately below the 0.10 m tillage depth with both NT and SM residue management practices. Cone index for NT and SM plots with PT was significantly less than the corresponding NOPT or ST plots. Benefits of the PT treatment to reduce cone index did not extend beyond the 0.35 m depth with either NT or SM residue management.

Mean soil profile (0.6 m depth) penetration resistance for all treatments varied from a cone index of 1.49 MPa for NT–PT to 1.99 MPa for SM–NOPT. Treatment combinations for NT and SM with NOPT had significantly greater penetration resistance than in corresponding PT plots, i.e., the cone index for NT–NOPT was 1.68 MPa and for SM–PT was 1.77 MPa. SM residue management and tillage treatment combinations had significantly greater penetration resistance than any NT treatment combination except NT–ST, 1.75 MPa. The corresponding 0.6 m profile volumetric soil-water contents in NT residue management plots were 0.31, 0.32, and 0.32 $m^3 m^{-3}$ for NOPT, PT, and ST, respectively, compared to 0.30 and 0.31 $m^3 m^{-3}$ for SM plots with NOPT and PT. Although water content varied significantly among treatments and can interact with penetration resistance measurements (Busscher et al., 1997), we statistically partitioned out the soil water effect as an ANOVA covariant (Christensen, 1987; Busscher et al., 1997).

Soil penetration resistance determined 23 months after PT and ST treatments, during fallow after wheat, were similar to observations at 12 months (data not shown). As noted for fallow after sorghum, mean profile soil-water contents to a 0.6 m depth at 23 months in NT plots were 0.30, 0.32, and 0.31 $m^3 m^{-3}$ for NOPT, PT, and ST, respectively, compared to similar water contents of 0.31 and 0.30 $m^3 m^{-3}$ for SM plots with NOPT and PT. Mean penetration resistance determined 23 months after PT and ST treatment for all residue management tillage treatments varied significantly from a minimum of 1.68 MPa for SM–PT to a maximum of 2.29 MPa for SM–NOPT. Similarly, cone index for the PT treatment within NT residue management of 1.72 MPa, was significantly less than 1.93 MPa for NOPT or 1.92 MPa for ST combinations. Benefits of PT reduced soil penetration resistance for longer than 23 months even though higher soil-water content after fallow diminished cone index differences. The diminished differences in cone penetration resistance index for tillage and residue management treatments 23 months after application could also be due to normal soil consolidation.

Soil cone penetration index was also compared in SM and NT residue management plots 31 months after NOPT, PT, and ST tillage treatment following sorghum harvesting. The soil was dry due to crop water use resulted in similar mean profile soil-water contents of 0.23, 0.23, and 0.24 $m^3 m^{-3}$ for NOPT, PT, and ST, respectively, in NT plots compared to 0.23 and 0.23 $m^3 m^{-3}$ for SM plots with NOPT and PT. The dry soil-water content tended to amplify differences in penetration resistance due to tillage

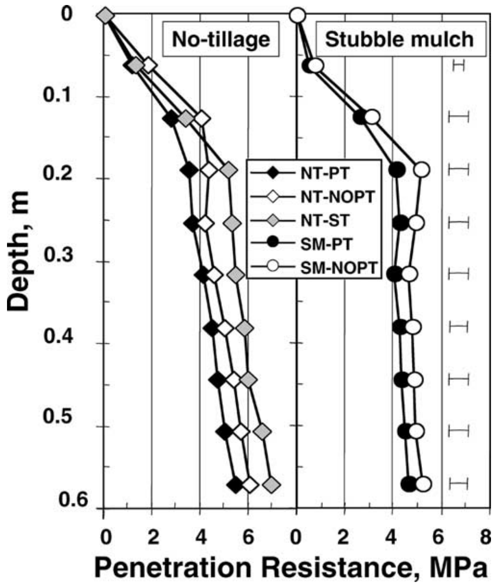


Fig. 4. Mean soil penetration resistance measured 31 months after treatment, plotted with depth for NT residue management plots receiving NOPT, PT, and ST, and for SM residue management plots receiving NOPT and PT. Error bars represent the pooled LSD ($P < 0.05$) by depth for all treatments.

and residue management. Except for the soil surface 0.0–0.15 m, the cone index plotted with depth in Fig. 4 was significantly greater with SM and tillage treatment combinations than NT–PT and NT–NOPT but not NT–ST. The mean profile cone index for SM–NOPT and SM–PT was 3.97 and 3.46 MPa, respectively, compared to 4.83 MPa for NT–ST. Cone index varied significantly in NT residue management plots at depths >0.10 m, i.e., the NOPT and ST tillage treatments had higher penetration resistance than with PT to the 0.35 m depth. As noted in SM, the soil loosening benefits of PT above the 0.35 m tillage depth decreased the mean soil profile cone penetration resistance index in NT from 4.32 for NOPT to 3.73 with PT.

Normal soil consolidation in these soils often negates deep tillage benefits for increasing infiltration (Baumhardt et al., 1993) or reducing soil penetration resistance (Unger, 1993). Our results show that PT reduced cone penetration resistance index for as long as 31 months, but repeated ST operations normally used with SM residue management may have compacted the soil and increased the cone index. Sustained reduction of penetration resistance with PT in NT residue management may suggest a method to promote deeper rooting. The benefit of chisel tillage to disrupt compacted soil layers and increase the volume of soil explored by roots resulted in both increased water use and, subsequently, crop yields (Doty and Reicosky, 1978).

### 3.2. Fallow soil-water storage

Precipitation amount and timeliness often govern water storage during fallow and supersedes the effects of tillage and residue management practices. Mean precipitation during fallow after sorghum and fallow after wheat (Table 2) was approximately double the 230 mm plant-available water that could potentially be stored in a 1.8 m Pullman clay loam profile. Limited fallow precipitation reduces soil-water storage and, consequently, decreases the fallow efficiency calculated as the ratio of water stored to fallow period precipitation. For example, of the 271 mm precipitation received during the 1990 fallow after sorghum only an average of 12% was stored. Precipitation storage was reduced during the 1990 and 1993 fallow after wheat periods even though precipitation was adequate. In this case, soil-water content at the start of fallow exceeded 156 mm or approximately 70% of the potential plant available water storage capacity and nearly double the mean initial fallow water content for the study. The remaining fallow periods in the study provide a better comparison to examine the combined effects of tillage and residue management practices on fallow precipitation storage.

The plant-available soil water stored during fallow after sorghum and fallow after wheat and the corresponding fallow efficiency listed in Table 2 were compared among the combined tillage and residue management treatments. Generally, the amount of precipitation stored as soil water and the calculated fallow efficiency was greater with NT compared to SM residue management particularly during fallow after wheat. The PT and ST tillage practices did not consistently improve soil-water storage. The 1990–1995 mean soil-water storage was not significantly different among tillage treatment combinations for either wheat or sorghum fallow periods.

These data show that precipitation storage amount and efficiency during fallow increased as the initial

Table 2
Paratill and residue-management effects on the amount of precipitation stored as plant-available soil water in the 0–1.8 m deep Pullman profile during fallow after sorghum and fallow after wheat using the WSF cropping sequence at Bushland, TX[a]

| Treatments[b] | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | mean |
|---|---|---|---|---|---|---|---|
| Fallow after sorghum | Fallow precipitation (mm) | | | | | | |
| | 271 | 376 | 681 | 444 | 460 | 485 | 453 |
| | Water stored (mm) | | | | | | |
| NT–NOPT | 35 (13) | 86 (23) | 158 (23) | 134 (30) | 134 (29) | 126 (26) | 112 (24) |
| NT–PT | 12 (4) | 95 (25) | 194 (28) | 149 (33) | 108 (23) | 146 (30) | 117 (24) |
| NT–ST | 21 (8) | 102 (27) | 160 (23) | 141 (32) | 104 (23) | 106 (22) | 106 (22) |
| SM–NOPT | 52 (19) | 76 (20) | 176 (26) | 137 (31) | 55 (12) | 90 (19) | 98 (21) |
| SM–PT | 41 (15) | 94 (25) | 196 (29) | 146 (33) | 50 (11) | 93 (19) | 103 (22) |
| LSD[c] ($P < 0.05$) | 19 | 36 | 38 | 23 | 45 | 19 | 30 |
| Fallow after wheat | Fallow precipitation (mm) | | | | | | |
| | 417 | 428 | 659 | 384 | 387 | 545 | 470 |
| | Water stored (mm) | | | | | | |
| NT–NOPT | −6 (−1) | 159 (37) | 213 (32) | 30 (8) | 104 (27) | 167 (31) | 111 (22) |
| NT–PT | 38 (−9) | 144 (34) | 208 (32) | 20 (5) | 133 (34) | 156 (29) | 116 (24) |
| NT–ST | 23 (−5) | 151 (35) | 196 (30) | 42 (11) | 110 (28) | 139 (25) | 110 (23) |
| SM–NOPT | −1 (−0) | 101 (24) | 197 (30) | 6 (2) | 68 (18) | 92 (17) | 77 (15) |
| SM–PT | 12 (−3) | 114 (27) | 206 (31) | −24 (−6) | 65 (17) | 127 (23) | 83 (16) |
| LSD ($P < 0.05$) | 18 | 55 | 22 | 21 | 18 | 40 | 29 |

[a] Values indicate water stored (mm) and the ones in the parentheses are the fallow efficiency, i.e., water stored divided by precipitation.
[b] Treatments are NT residue management plots receiving NOPT, PT, and ST, and SM residue management plots receiving NOPT and PT.
[c] The least significant difference (LSD) is reported at the ($P < 0.05$) level.

soil-water content decreased and as precipitation amount increased. Management practices that increase soil residue cover also increased precipitation storage. That is, water storage during fallow tended to increase with NT residue management, which reduced evaporation and probably protected the soil from infiltration limiting crust formation. Subsoil tillage practices to increase soil water movement, however, were less effective for improving precipitation storage during fallow.

### 3.3. Soil water at planting

Available soil water at wheat and sorghum planting is listed for 1990–1995 in Table 3. At wheat planting, i.e., end of fallow after sorghum, the combination tillage and residue management treatments resulted in no consistent differences in tillage and residue management treatment combinations. For example, the NT–PT management combination during fallow after sorghum resulted in both the largest and the smallest water contents observed at wheat planting during this 6-year study. The mean 1990–1995 soil-water content of each tillage and residue management combination was not significantly different. Management of sorghum residue with NT or SM achieved no consistent differences in water conserved for use by wheat at planting. During years when adequate fallow precipitation occurred at or near the end of the fallow period, the soil water at planting approached the potential storage capacity. In contrast, water storage increased with NT even when precipitation was limited during the end of fallow, or when precipitation was limited throughout the entire fallow phase, probably because of reduced evaporation. Soil-water storage was not increased by PT and, occasionally, decreased water storage when subsoil tillage exposed moist soil at greater depths to drying conditions.

Soil water at sorghum planting, i.e., end of fallow after wheat, for the tillage and residue management combinations is listed in Table 3. In contrast to fallow after sorghum, the soil is more completely covered by residues during the fallow after wheat phase, which reduces evaporation. Soil-water storage was consistently greater with NT residue management than with SM, which incorporates some residue. The differences

Table 3
Tillage and residue-management effects on the amount of plant-available soil water for the 0–1.8 m deep Pullman profile at sorghum and wheat planting after fallow of the WSF cropping sequence at Bushland, TX

| Treatments[a] | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | Mean |
|---|---|---|---|---|---|---|---|
| Fallow after sorghum[b] | | | | | | | |
| NT–NOPT | 202 | 115 | 201 | 210 | 199 | 202 | 188 |
| NT–PT | 247 | 84 | 204 | 241 | 209 | 170 | 192 |
| NT–ST | 181 | 102 | 223 | 197 | 203 | 170 | 179 |
| SM–NOPT | 181 | 132 | 213 | 212 | 194 | 109 | 173 |
| SM–PT | 177 | 125 | 214 | 220 | 202 | 105 | 174 |
| LSD[c] ($P < 0.05$) | 31 | 21 | 18 | 25 | 14 | 18 | 21 |
| Fallow after wheat[d] | | | | | | | |
| NT–NOPT | 150 | 152 | 238 | 190 | 167 | 206 | 184 |
| NT–PT | 195 | 142 | 235 | 188 | 204 | 200 | 194 |
| NT–ST | 177 | 150 | 222 | 206 | 178 | 186 | 186 |
| SM–NOPT | 156 | 107 | 222 | 178 | 135 | 138 | 156 |
| SM–PT | 168 | 129 | 231 | 150 | 139 | 174 | 165 |
| LSD ($P < 0.05$) | 18 | 30 | 14 | 13 | 20 | 18 | 19 |

[a] Treatments are NT residue management plots receiving NOPT, PT, and ST, and SM residue management plots receiving NOPT and PT.
[b] Plant available water at wheat planting (mm).
[c] The LSD is reported at the ($P < 0.05$) level.
[d] Plant available water at sorghum planting (mm).

in soil-water content at planting for the subsoil tillage combinations with NT residue management were significantly greater than for the corresponding SM residue management combinations for 1993–1995 and the overall 1990–1995 mean. Loosening the soil with ST and PT in NT residue management plots did not consistently increase soil water at planting over NOPT due to increased evaporation from tillage-disturbed soil. Reicosky et al. (1999) documented increased fluxes of both $CO_2$ and water from a conventionally tilled loamy sand after chisel plowing had exposed moist soil channels. Similarly, PT used with SM residue management did not consistently increase water storage because increased evaporation during dry years offset the benefits of improved water movement into the profile during years with greater rainfall.

The 1990–1995 mean soil-water content with depth is plotted at wheat and sorghum planting in Fig. 5. The principal difference in available soil water was due to residue management treatment effects, i.e., less water had been stored with SM compared to NT residue management during either sorghum or wheat planting. The increased soil water observed in NT residue management plots was apparent at greater soil profile depths and beyond the depth of subsoil tillage treatments. No significant differences in available soil water at planting due to PT or ST tillage treatments were observed within NT or SM residue management for either sorghum or wheat. These data suggest that residue management and not subsoil tillage will significantly increase the amount of soil water available at planting.

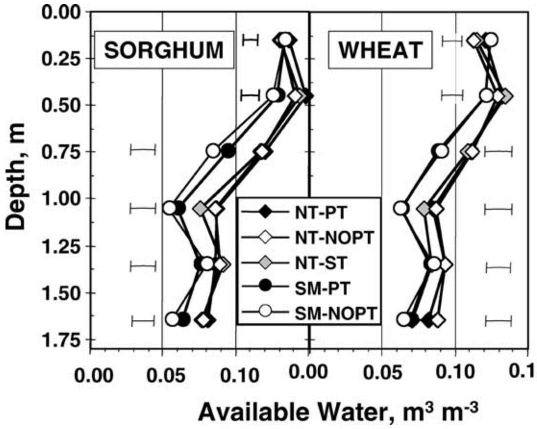


Fig. 5. The 1990–1995 mean plant available water content ($m^3\,m^{-3}$) at sorghum and wheat planting, plotted with depth for NT residue management plots receiving NOPT, PT and ST, and for SM residue management plots receiving NOPT and PT. Error bars represent the pooled LSD ($P < 0.05$) by depth for all treatments.

Table 4
Tillage and residue-management effects on water use, yield, and WUE of wheat grown using the WSF rotation at Bushland, TX (1990–1995)

| Treatments[a] | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | Mean |
|---|---|---|---|---|---|---|---|
| Precipitation (mm) | 129 | 250 | 486 | 240 | 214 | 285 | 269 |
| Water used (mm) | | | | | | | |
| NT–NOPT | 315 | 343 | 536 | 381 | 351 | 450 | 396 |
| NT–PT | 369 | 289 | 521 | 407 | 376 | 408 | 395 |
| NT–ST | 329 | 331 | 549 | 375 | 380 | 400 | 394 |
| SM–NOPT | 310 | 340 | 522 | 381 | 377 | 361 | 382 |
| SM–PT | 300 | 366 | 524 | 393 | 367 | 368 | 386 |
| LSD[b] ($P < 0.05$) | 56 | 44 | 44 | 48 | 32 | 57 | 45 |
| Yield ($Mg\,ha^{-1}$) | | | | | | | |
| NT–NOPT | 1.99 | 1.46 | 3.26 | 2.07 | 1.91 | 0.80 | 1.92 |
| NT–PT | 2.16 | 1.43 | 3.43 | 2.27 | 2.16 | 0.73 | 2.03 |
| NT–ST | 2.09 | 1.47 | 3.48 | 1.89 | 2.19 | 0.84 | 1.99 |
| SM–NOPT | 2.87 | 1.85 | 3.80 | 1.51 | 2.11 | 0.28 | 2.07 |
| SM–PT | 2.57 | 1.85 | 3.61 | 1.48 | 1.99 | 0.38 | 1.98 |
| LSD ($P < 0.05$) | 0.26 | 0.16 | 0.60 | 0.28 | 0.17 | 0.18 | 0.54 |
| WUE ($kg\,m^{-3}$) | | | | | | | |
| NT–NOPT | 0.64 | 0.43 | 0.61 | 0.54 | 0.55 | 0.18 | 0.49 |
| NT–PT | 0.59 | 0.50 | 0.66 | 0.56 | 0.58 | 0.18 | 0.51 |
| NT–ST | 0.65 | 0.44 | 0.63 | 0.51 | 0.58 | 0.21 | 0.50 |
| SM–NOPT | 0.93 | 0.55 | 0.73 | 0.40 | 0.56 | 0.08 | 0.54 |
| SM–PT | 0.86 | 0.51 | 0.70 | 0.38 | 0.54 | 0.10 | 0.51 |
| LSD ($P < 0.05$) | 0.11 | 0.07 | 0.13 | 0.08 | 0.06 | 0.04 | 0.12 |

[a] Treatments are NT residue management plots receiving NOPT, PT, and ST, and SM residue management plots receiving NOPT and PT.
[b] The LSD is reported at the ($P < 0.05$) level.

### 3.4. Crop yield, water use, and WUE

Residue management and tillage effects on wheat yield and water use estimated as the sum of precipitation and the change in soil-water content during the growing season are reported in Table 4. The 1990–1995 growing season precipitation ranged from 129 to 486 mm with water use varying from 289 to 549 mm. Long term, 1958–2000, precipitation during the wheat-growing season at Bushland, TX, is 267 mm or approximately the same as the 269 mm average during this 6-year test. Seasonal crop water use varied significantly due to tillage and residue effects during half of the years, but no consistent trend emerged and the water use averaged for the study did not differ among treatments. That is, the average water use by wheat during the study with NT (395 mm) residue management was not different from SM (384 mm). Similarly, subsoil tillage to increase water storage and root proliferation through the soil profile by PT achieved no significant difference in water use compared to NOPT or ST tillage treatments.

The benefits of residue management and tillage to increase available soil water are integrated by the crop resulting in greater yields and improved WUE. Under dryland conditions, however, the effect of precipitation timeliness often confounds yield indications. For example, the lowest wheat grain yields reported in 1995 were not associated with the lowest growing season precipitation of 129 mm observed in 1990 (Table 4). The greatest seasonal precipitation (486 mm) and water use (>521 mm) in 1992 diminished all treatment effects, but resulted in excellent overall average dryland wheat yields of 3.55 $Mg\,ha^{-1}$. The combination tillage and residue management practices induced significant yield differences during the other years tested; however, no consistent treatment effect emerged. That is, wheat yield with SM residue management was greater than with NT during 1990 and 1991, but less during 1993 and 1995. The use of PT and ST for subsoil tillage did not significantly increase wheat yield compared to NOPT in the NT plots where penetration resistance was large. Although not significant, SM plots receiving NOPT tended to have higher yield compared to PT, which apparently accelerated soil-profile drying. The resulting overall 1990–1995 mean wheat yields did not vary significantly with tillage and residue management combinations.

The corresponding wheat WUE calculated as the ratio of grain yield (kg) to the amount of water used ($m^{-3}$) during the growing season, generally, mirrored yield differences, i.e., WUE increased with increasing yields (Table 4). But, WUE varies with precipitation timeliness, e.g., the lowest WUE of approximately 0.2 kg $m^{-3}$ was observed in 1995 with 285 mm seasonal precipitation compared to WUE $> 0.59$ kg $m^{-3}$ observed in 1990 with the lowest (129 mm) but timely seasonal precipitation. Calculated WUE of the tillage and residue treatment combinations frequently grouped by residue management practices with NT being greater than SM in 1993 and 1995, but reversed in 1990 and 1991. No consistent PT or ST subsoil tillage effect on WUE was determined. The 1990–1995 mean WUE varied from 0.49 to 0.54 kg $m^{-3}$ or approximately the same as 0.48 to 0.51 kg $m^{-3}$ calculated for wheat using water use and yield data of a 16-year study at Bushland, TX (Baumhardt et al., 2000).

Precipitation, water use, yield, and WUE of sorghum are listed in Table 5 by tillage and residue management treatment combinations for the years 1990–1995. Measured growing season precipitation during the study varied from 222 to 340 mm and averaged 268 mm, or about the same as the 260 mm long term, 1958–2000, sorghum-growing season precipitation at Bushland, TX. Seasonal sorghum water use varied from 264 to 462 mm, but tillage and residue effects were inconsistent and no trend emerged. The mean 1990–1995 water use for the study were not significantly different among treatments. The average sorghum water use was 383 mm with NT residue

Table 5
Tillage and residue-management effects on water use, yield, and WUE of sorghum grown using the WSF rotation at Bushland, TX (1990–1995)

| Treatments[a] | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | Mean |
|---|---|---|---|---|---|---|---|
| Precipitation (mm) | 222 | 260 | 282 | 241 | 340 | 265 | 268 |
| Water used (mm) | | | | | | | |
| NT–NOPT | 264 | 357 | 455 | 368 | 455 | 380 | 380 |
| NT–PT | 321 | 373 | 440 | 380 | 440 | 384 | 390 |
| NT–ST | 277 | 365 | 448 | 361 | 436 | 381 | 378 |
| SM–NOPT | 271 | 331 | 452 | 367 | 406 | 344 | 362 |
| SM–PT | 267 | 361 | 462 | 338 | 423 | 367 | 370 |
| LSD[b] ($P < 0.05$) | 31 | 58 | 19 | 22 | 42 | 46 | 36 |
| Yield (Mg $ha^{-1}$) | | | | | | | |
| NT–NOPT | 1.07 | 4.02 | 5.06 | 3.60 | 4.18 | 3.32 | 3.54 |
| NT–PT | 0.93 | 3.87 | 4.65 | 3.00 | 4.01 | 2.85 | 3.22 |
| NT–ST | 0.90 | 4.01 | 3.98 | 2.89 | 4.10 | 3.14 | 3.17 |
| SM–NOPT | 0.47 | 2.99 | 5.35 | 2.60 | 3.20 | 2.32 | 2.82 |
| SM–PT | 0.58 | 3.27 | 5.76 | 2.84 | 3.32 | 2.78 | 3.09 |
| LSD ($P < 0.05$) | 0.19 | 0.41 | 0.65 | 0.74 | 0.44 | 0.38 | 0.79 |
| WUE (kg $m^{-3}$) | | | | | | | |
| NT–NOPT | 0.41 | 1.13 | 1.11 | 0.98 | 0.92 | 0.88 | 0.90 |
| NT–PT | 0.29 | 1.05 | 1.06 | 0.79 | 0.92 | 0.75 | 0.81 |
| NT–ST | 0.33 | 1.11 | 0.89 | 0.81 | 0.94 | 0.83 | 0.82 |
| SM–NOPT | 0.18 | 0.91 | 1.18 | 0.71 | 0.79 | 0.68 | 0.74 |
| SM–PT | 0.22 | 0.93 | 1.25 | 0.84 | 0.79 | 0.76 | 0.79 |
| LSD ($P < 0.05$) | 0.07 | 0.20 | 0.13 | 0.22 | 0.14 | 0.13 | 0.12 |

[a] Treatments are NT residue management plots receiving NOPT, PT, and ST, and SM residue management plots receiving NOPT and PT.
[b] The LSD is reported at the ($P < 0.05$) level.

management compared to 366 mm with SM. Similarly, PT and ST subsoil tillage increased mean water storage compared to NOPT by less than 10 mm during the study.

Dryland sorghum grain yield varied from 0.47 to 5.76 Mg ha$^{-1}$, increasing as the amount of precipitation and/or stored soil water increased to meet the crop water use demand (Table 5). Because of more complete soil coverage by wheat residue during fallow that was consistently greater with NT (data not shown), the subsequent sorghum yields were significantly greater 4 of the 6 years for tillage combinations with NT compared to SM residue management. Grain yield in NT plots were typically higher with NOPT compared to PT and ST subsoil tillage, which was attributed to soil profile disturbance and, consequently, soil drying. Alternatively, PT consistently increased grain yield in SM plots that may have been compacted by the stubble-mulch sweep-plowing operations. That is, PT may have relieved soil compaction in SM plots; thus permitting more extensive rooting and greater water use. These offsetting trends resulted in no significant yield benefit when using PT subsoil tillage during any year. The 1990–1995 mean grain yields were not significantly different among the combined tillage and residue management treatments. These data show that residue management has a much larger effect on dryland grain yield than does subsoil tillage.

Sorghum WUE varied from a high of 1.25 kg m$^{-3}$ in 1992 with >440 mm water use to a low of 0.18 kg m$^{-3}$ during the 1990 "drought" when the 222 mm precipitation accounted for >75% of the crop water use. The WUE tended to be greater with NT residue management treatment combinations compared to SM residue management, resulting in higher 1990–1995 mean WUE for NT plots. As with yield, the WUE tended to be greater with NOPT in NT plots and PT in SM plots. No significant benefit of PT compared to NOPT was observed for any year. These data show that WUE, like yield, was increased with residue management that reduced evaporation. No benefit in water use or crop yield was attributed to subsoil tillage method.

## 4. Conclusions

Grain production with the WSF rotation is principally related to precipitation storage as soil water during fallow, i.e., increased soil water at planting. The amount and efficiency of soil-water storage during fallow was greater after wheat compared to sorghum and increased with NT compared to SM residue management practices. Wheat residue provides more complete soil cover compared to sorghum and NT more efficiently reduces evaporation from the soil than SM, which opens the surface for evaporation. In both NT and SM residue management practices, PT compared to NOPT did not consistently increase the amount of soil water available to the wheat and sorghum crops. Infiltration, and hence storage of precipitation as soil water, was quickly regulated by developing soil surface crusts that were unaffected by PT subsoiling. A similar result was noted by Baumhardt et al. (1992) for chisel tillage subsoiling in coarse textured soil. Soil profile loosening with PT or ST reduced cone penetration resistance index compared to NOPT, which suggests that increased potential crop root proliferation and soil exploration could result in greater yields. Our results, however, show that the yields of dryland wheat and sorghum were unaffected by tillage treatment combinations that reduced the penetration resistance possibly because root growth was not limited. Similar observations were made for irrigated sorghum tests (Allen and Musick, 1997, 2001). We conclude that residue management is much more important to dryland grain production than is PT and ST subsoil tillage.

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